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FRACTURE TOUGHNESS OF FATIGUE-DAMAGED STEEL SPECIMENS.(U)
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FRACTURE TOUGHNESS OF FATIGUE-DAMAGED STEEL SPECIMENS

Graham Clark

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6) FRACTURE TOUGHNESS OF FATIGUE-DAMAGED STEEL SPECIMENS

10) Graham Clark

11) Jun 79

ABSTRACT

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The plane strain fracture toughness (K_{Ic}) of a material is used to describe the crack tip conditions required for unstable growth of a crack, and is used extensively in designing metallic components and in assessing the severity of pre-existing defects. There are many situations in service, however, where the crack tip stress conditions immediately prior to unstable crack growth are not identical to those in a standard fracture toughness test specimen. This report examines the fracture toughness of high-quality gun steel, and describes conditions under which the fatigue pre-cracking levels specified for K_{Ic} tests may produce unreasonably high values of K_{Ic}, leading to an increased possibility of in-service fracture of components designed using these values.

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POSTAL ADDRESS: Chief Superintendent, Materials Research Laboratories P.O. Box 50, Ascot Vale, Victoria 3032, Australia

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DOCUMENT CONTROL DATA SHEET

Security classification of this page: UNCLASSIFIED

1. DOCUMENT NUMBERS:	2. SECURITY CLASSIFICATION:
a. AR Number: AR-001-827	a. Complete document: UNCLASSIFIED
b. Series & Number: REPORT MRL-R-749	b. Title in isolation: UNCLASSIFIED
c. Report Number: MRL-R-749	c. Abstract in isolation: UNCLASSIFIED

3. TITLE:

FRACTURE TOUGHNESS OF FATIGUE-DAMAGED STEEL SPECIMENS

4. PERSONAL AUTHOR(S): CLARK, Graham	5. DOCUMENT DATE: JUNE, 1979
	6. TYPE OF REPORT & PERIOD COVERED:
7. CORPORATE AUTHOR(S): Materials Research Laboratories	8. REFERENCE NUMBERS: a. Task: DST 77/069 b. Sponsoring Agency:
	9. COST CODE: 514720
10. IMPRINT (Publishing establishment) Materials Research Laboratories, P.O. Box 50, Ascot Vale, Vic.3032 JUNE, 1979	11. COMPUTER PROGRAMME(S): (Title(s) and language(s)):

12. RELEASE LIMITATIONS (of the document):

Approved for Public Release

12-0. OVERSEAS: N.O. [ ] P.R. [1] A [ ] B [ ] C [ ] D [ ] E [ ]

13. ANNOUNCEMENT LIMITATIONS (of the information on this page):

No Limitation

14. DESCRIPTORS: 630 Crack Propagation 636 Fracture Toughness Fatigue Damage 645 Gun Steels High Strength Low Alloy Steels Crack Tip Stress Pre-cracking Tests

15. COSATI CODES: 1106 1113 2012

16. ABSTRACT (if this is security classified, the announcement of this report will be similarly classified):

The plane strain fracture toughness (K_{Ic}) of a material is used to describe the crack tip conditions required for unstable growth of a crack, and is used extensively in designing metallic components and in assessing the severity of pre-existing defects. There are many situations in service, however, where the crack tip stress conditions immediately prior to unstable crack growth are not identical to those in a standard fracture toughness test specimen. This report examines the fracture toughness of high-quality gun steel, and describes conditions under which the fatigue pre-cracking levels specified for K_{Ic} tests may produce unreasonably high values of K_{Ic}, leading to an increased possibility of in-service fracture of components designed using these values.

NOTATION

K_I	Plane strain stress-intensity factor
K_{Ic}	Plane strain fracture toughness
K_Q	Non-validated value of fracture toughness
K_f	Maximum stress-intensity during fatigue-cracking
ΔK	Alternating stress-intensity (= $K_{max}-K_{min}$ of fatigue cycle)
σ_c	Critical value of applied stress
σ_y	0.2% offset proof stress
r	Plastic zone size
a	Crack length
a_c	Critical half-length of a crack
a_o, a_t	Initial, final crack lengths
α	Factor specified in fracture toughness test, $K_f = \alpha K_Q$
A	Geometrical factor
W	Specimen width
B	Specimen thickness
T	Gun barrel wall thickness
P_Q	Value of critical load in fracture toughness test
P_{max}	Maximum load in K_{Ic} test
P	Bore pressure in gun barrel
N	Number of fatigue cycles
F(a/T)	Crack multiplicity factor in gun barrel stress-intensity calibration

CONTENTS

* * *

FRACTURE TOUGHNESS OF FATIGUE-DAMAGED STEEL SPECIMENS

1. INTRODUCTION

1.1 Fracture Toughness

In designing metallic structures it is usually desirable that the structure has minimum weight and maximum load-bearing capacity. One means of achieving both of these objectives is the increased use of high strength material, and improvements in strength-to-weight ratio have been achieved by the use of high strength low alloy (HSLA) steels for structural purposes. Unfortunately, without improvement in steel quality, any significant increase in the strength of a steel almost invariably results in a lower toughness, and it is increasingly important to ensure that structures containing high strength steels will not fail by the unstable growth of a pre-existing defect. For reasonably thick sections, this involves determination of the plane strain fracture toughness, K_{Ic}, of the material, by means of a carefully standardised laboratory testing procedure [1,2].

The material property K_{Ic} defines the magnitude of the stress system around the tip of a crack at instability, and the stress-intensity at the tip of a defect in a real structure must not exceed this value.

At instability, the stress-intensity factor

$$K_I = K_{Ic} = A \sigma_c \sqrt{\pi a_c} \tag{1}$$

where A is a factor reflecting the geometry of the test specimen and loading system. Clearly, for a known applied stress there exists a critical value of crack length which must not be exceeded, and a typical program to ensure the integrity of a structure would involve inserting known values of K_{Ic} and σ_c in eqn (1) and hence determining the critical crack length. Inspection of the structure would reveal any cracks approaching this length, and regular inspection would be arranged to ensure that a shorter crack (a sub-critical crack) could not grow to the critical length by fatigue cycling or by environmentally-assisted cracking. An alternative procedure involves analyzing known defects using eqn (1) with the intention of limiting the loads on the structure.

1.2 Fracture Toughness Testing

In order to guarantee fracture safety, it is essential that reliable K_{Ic} values should be available at the design stage, and it follows that the reliability of plane strain fracture toughness testing procedures is of great importance.

The K_{Ic} test is specified [1,2] and discussed in detail [3,4] elsewhere. In brief, the test consists of loading one of a variety of specimens and measuring crack mouth displacement. One specimen design (the compact specimen) is shown in Fig. 1, and loading in this instance is in tension, via pins through the holes which are located on each side of the notch. Application of a cyclic load causes growth of a fatigue crack from the root of the machined notch, until the crack length/specimen width (a/W) ratio lies between 0.45 and 0.55. After fatigue cycling, a displacement gauge is attached to the mouth of the notch, and the specimen is loaded in tension, providing a force-displacement trace from which critical force values are later determined. After testing, the specimen is broken open, and the a/W ratio at the beginning of the test is determined from the fracture surface.

The force-displacement record may take several forms [1,2], that of interest here being shown in Fig. 2. A secant is drawn at 5% less slope than the initial slope of the trace, and the intersection of this line with the trace defines a tentative value (P_Q) of the critical load for crack extension. This load may now be used with a compliance calibration $f\left(\frac{a}{W}\right)$ given in references [1] and [2], in

$$K_Q = \frac{P_Q}{BW^{\frac{1}{2}}} \cdot f\left(\frac{a}{W}\right) \qquad (2)$$

to determine a tentative value (K_Q) of the plane strain fracture toughness. B and W are thickness and effective specimen width respectively.

The test record must now meet several conditions before K_Q may be assumed to be a valid K_{Ic} determination, including the following :

$$\text{(a)} \quad a \geqslant 2.5\,(K_Q/\sigma_y)^2 \text{ where } \sigma_y = \text{yield strength} \qquad (3)$$

to ensure that the yield zone at the crack tip is small compared with the crack length. This condition is necessary because the stress-intensity factor expression is in fact a series of which only the first term is normally taken.

$$\text{(b)} \qquad B \geqslant 2.5\,(K_Q/\sigma_y)^2 \qquad (4)$$

to ensure that the crack tip yield zone is small compared with the specimen thickness. If this is not the case, through-thickness yielding may be significant and plane strain conditions cannot be assumed.

(c) The maximum stress-intensity used during fatigue cycling (K_f) must satisfy

$$K_f \leqslant \alpha \, K_Q \qquad (5)$$

where the term $\alpha = 0.6$ in reference [1] and 0.7 in reference [2].

1.3 K_{Ic} Testing Using High K_f Levels

The fracture toughness test is performed on a fatigue-cracked specimen in order that the most severe stress-concentration possible will occur at the crack tip. However, it was noted by Brown and Srawley [3] that fatigue-cracking at high levels of K_f leads to increased values of K_Q. Their results suggested that this effect may only be neglected in maraging steel when $K_f \leqslant 0.35 \, K_Q$. The form of the proposed K_{Ic} test at that time [5] used a limit of $\alpha \leqslant 0.5$, and when Brown and Srawley [6] noted that their earlier results had been in error (the experimentally determined limit should have been $\alpha = 0.6$) a value of $\alpha \leqslant 0.6$ was adopted in a revised version of the proposed test method [7], and ultimately in the standard [1].

May [8,9] reported the results of similar tests on three low-alloy steels and concluded that values of α up to 0.8 or 0.9 were permissible, with no significant effect on K_Q. A very conservative $\alpha \leqslant 0.5$ condition was proposed, and the condition $\alpha \leqslant 0.67$ was subsequently specified in a draft British Standard [10]. In the full standard [2] this has been further modified to $\alpha \leqslant 0.7$.

Kaufman [11] reported the results of tests on four aluminium alloys, indicating that $\alpha \leqslant 0.8$ would be suitable criterion, and proposed a condition for general use, of $\alpha \leqslant 0.75$.

The values of α specified in current standards for K_{Ic} testing [1,2] have been deduced from tests on a limited number of materials, many of which were ultra-high strength, low-toughness materials, such as maraging steels, for which valid K_{Ic} tests can be performed on relatively small and convenient specimens. The region ahead of the crack which is subjected to cyclic plasticity has a size controlled by K_f and σ_y, according to

$$r \quad \propto \quad (K_f/\sigma_y)^2 \qquad (6)$$

and hence in these high strength materials an element of undeformed material remote from the crack will be subjected to very few cycles of plastic strain before being passed by the crack tip. In contrast, such an element in a material of lower yield strength will undergo many more cycles, and will

more closely approach cyclic stability. Specimens of such a material would be expected to show maximum sensitivity to the maximum fatigue levels used to prepare a K_{Ic} test specimen. A similar argument will apply to the size of the region subjected to reversed cyclic plasticity

$$r \quad \propto \quad (\Delta K/\sigma_y)^2 \tag{7}$$

and it is clear that the use of different values of ΔK for pre-cracking a K_{Ic} test specimen, with a constant K_f, might also affect the subsequent behaviour of the crack tip material.

This report discusses tests on high-quality gun steels (of medium to high strength, and of a type similar to many high-strength steels used increasingly for engineering purposes) in which the appropriate value of α is determined, in order that unreasonably high K_Q determinations are not accepted as valid fracture toughness values.

1.4 Significance of Increased K_Q Values

The majority of engineering failures originate at a fatigue crack, and whilst in some of these cases a severe overload is responsible for catastrophic failure, there are many cases in which the fatigue crack simply grows, under more or less uniform cyclic loading, to failure. These are exactly the conditions experienced in a K_{Ic} test which has been prepared at high fatigue stress-intensities, and it would therefore be more appropriate to use the *increased* K_Q which would result from such a test, in the practical case. Clearly, the actual value of critical stress-intensity (K_Q) to be used in service will be governed by the fatigue stress-intensity applied over the last few millimetres of crack growth, and this in a practical case will usually be determined by the presence (or otherwise) and magnitude of overload transients in the loading cycle.* In many cases, changes in loading might well occur as a result of growth of the crack itself (by load transfer to other parts of the structure) and the stress-intensity 'history' of the crack tip could be relatively complex.

In the experimental work described below, the increase in K_Q due to fatiguing at high stress-intensities is determined, in order to assess the practical effect of such an increase upon critical crack length. An example is given of the way in which this increase would affect the fatigue life of a component.

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* The highest K_Q would be used for the case in which a crack grows under uniform cyclic loading, with no overloads, to failure.

2. EXPERIMENTAL WORK

Compact fracture toughness specimens of two high-quality low-alloy steels were machined, with a thickness of 25.4 mm, and an initial crack length-to-specimen width of 0.3. Material composition and tensile data are given in Tables I and II. Specimens of one material (A) were machined in the same orientation from adjacent positions within a fully heat-treated large forging, in order to ensure uniformity of properties, whereas specimens of material B were heat-treated between rough machining and final machining operations. Eighteen specimens of material A and seven of B were prepared and tested in accordance with the requirements of ASTM E399-74 [1], with the exception of the fatigue-cracking load requirement.

Fatigue cracking and monotonic testing were carried out in a 500 kN MTS servohydraulic testing machine, using a clevis tension system as described by ASTM [1]. Fatigue-cracking was carried out at frequencies between 2.5 and 15 Hz, the lower frequencies being used at longer crack lengths and higher stress-intensities.

Crack lengths during fatigue cracking were monitored using an electrical potential system [12] which made it possible to grow fatigue cracks to the same length in each specimen $\left(\frac{a}{W} = 0.510 \pm 0.013\right)$ with ease. Excluding the fatigue-crack loading conditions, all test records were analyzed according to ASTM E399-74, and this analysis resulted in the rejection of two specimens of material A, fatigued at low stress-intensities, on the grounds that P_{max}/P_Q exceeded 1.10. These two results are not included in this report.

It was not possible to apply condition (b) regarding the thickness requirement of E399-74, as the appropriate flow stress for specimens in which cyclic hardening or softening is considerable is not available, but it should be noted that if the monotonic yield stress is used, only those specimens fatigued at the lowest stress-intensities are valid K_{Ic} tests. Further work is needed to investigate this point.

3. RESULTS AND DISCUSSION

Figure 3 shows the variation in K_Q with increasing K_f for materials A and B. Also indicated are lines representing ASTM and BSI limiting values of α (namely 0.60 and 0.70 respectively), together with lines representing $\alpha = 0.50$ and $\alpha = 1.0$. The results show that, in order to guarantee a conservative value of K_{Ic}, there is a case for further limitations on permitted fatigue-cracking loads; the data in Fig. 3 suggests that a suitable criterion is $K_f \leq 0.5\ K_Q$. It is clear that there is a considerable increase in K_Q as K_f approaches K_Q, the maximum increase being approximately 40% in material A, and when the relationship between fracture toughness and critical crack length

$$K_{Ic}^2 \propto a_c \tag{8}$$

is considered, the increase in K_Q can be seen to correspond to an increase in a_c of over 90%. While neglecting this effect during design or defect assessment in a component subjected to uniform cyclic loading would simply increase the margin of safety in the structure, it is nevertheless important from the point of view of efficient design to be able to estimate the true critical crack length as closely as possible. In situations involving only small transient overloads (such as in turbine discs and shafts) the appropriate increase in critical crack length may be determined by laboratory tests such as those described here, and applied during design.

It is interesting to note that material A will tolerate a higher stress-intensity in fatigue than the value K_Q normally used to define instability, this effect also being noted by May [8,9], whose results indicated that K_f may in some cases exceed K_Q by as much as 40%. This would appear to question the usefulness in such cases of a failure criterion based on the K_{Ic} testing procedure - it would seem, in fact, that a more appropriate failure criterion might well be the actual value of K_Q recorded. It should be noted, however, that such an effect would only be likely in materials which exhibit the "ductile" form of the load-displacement trace, and that it is unlikely that K_f could exceed K_Q by more than approximately 10% without incurring rejection of the test record on the grounds that P_{max}/P_Q exceeds 1.10 (i.e. that there is excessive plasticity during the test).

The reasons for the observed increase in K_Q are clearly complex, but it would seem that attributing the effect to simple crack blunting [6] is not sufficient. While increasing the radius of an undamaged crack tip *does* lead to an increase in apparent toughness, blunting of a sharp crack by a simple monotonic loading would not be expected to have much effect on the load-displacement trace recorded after this load has been exceeded during a subsequent test, on the grounds that the specimen should be capable of undergoing multiple low-level pre-loads in an approximately elastic manner. The important factor is to be considered however, is cyclic hardening (or softening) which can cause gross changes in the fracture behaviour of the crack tip material, and it is suggested that any detailed study of this effect would require evaluation of the cyclic properties of the material investigated.

Example

With the increased use of high-strength steels in the manufacture of large-calibre gun barrels, there has been an increase in the probability of such barrels failing by catastrophic fracture from a fatigue crack. These cracks grow from the network of thermal craze cracks which is established in the first few rounds of barrel life, and it is important to be able to predict the number of cycles required to cause failure. Here we consider a simplified and somewhat idealised version of a model discussed elsewhere [13].

The barrel considered is a high strength large-calibre gun barrel for which the fracture toughness and fatigue-crack growth properties are known; K_{Ic} is approximately 110 MPa $\sqrt{m}$ and the crack growth rate (in metres per

cycle) is given approximately by the Paris [14] equation

$$da/dN = 3.378 \times 10^{-26} \ (\Delta K)^{2.5} \tag{9}$$

We assume [13] that the crack array consists of 40 equal (and equally-spaced) cracks around the bore, and in this report no crack shape correction is applied. The stress-intensity calibration for an array of 40 cracks is documented [15] and is used as follows :

$$K = P \sqrt{a} \ . \ F(a/T) \tag{10}$$

where P is the firing pressure, a/T is the crack-length/wall-thickness ratio, and F(a/T) is the appropriate calibration [15].

If the appropriate value of fracture toughness is used in eqn (10), a value of critical crack length (a_f/T) may be readily determined, and this value may then be used to estimate the number of cycles to cause failure, by integration of eqn (9).

Corresponding values of fracture toughness, critical crack length and number of cycles to failure are given below using a K_{Ic} of 110 MPa $\sqrt{m}$ and a value of toughness which is increased by 40%, as was observed above for conditions of high-level uniform fatigue loading.

Toughness	a_f/T	N
110 MPa $\sqrt{m}$	0.25	8 850
154 MPa $\sqrt{m}$	0.6	15 330

It is clear that a major increase in critical crack length and fatigue life would be observed in such a case if the conditions described above were met. Note however that various other factors which affect the life of a barrel, such as the tendency for one crack to advance faster than the rest of the array, have been ignored in this idealised example, and hence the fatigue lives given by this analysis must be regarded as upper-bound estimates. In addition, factors such as variations in charge pressure would tend to reduce the 40% increase in toughness value used here. However there is a clear case for further research to determine the fatigue conditions and materials for which an increased toughness value may be used.

4. CONCLUSIONS

For the materials tested, a suitable criterion for pre-cracking fracture-toughness test specimens is $K_f \leqslant 0.5\ K_Q$. This is a more conservative criterion that those currently required by fracture toughness test procedures.

Fracture toughness testing of two high-quality low-alloy steels after pre-cracking at high fatigue load levels results in an increase in critical crack length of approximately 90%. This increased value may be used in the design of components which are to be used under conditions of high uniform cyclic loading, and may result in large increases in estimates of component fatigue life.

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TABLE I

APPROXIMATE COMPOSITION OF STEELS A AND B

	C	Si	Mn	P	S	Cr	Mo	Ni
A	0.32	0.23	0.58	0.005	0.01	0.87	0.54	3.06
B	0.32	0.25	0.64	0.006	0.005	0.74	0.47	2.56

TABLE II

TENSILE DATA FOR STEELS A AND B (MPa)

	0.2% Offset Yield Stress	UTS
A	1100	1186
B	1120	1270

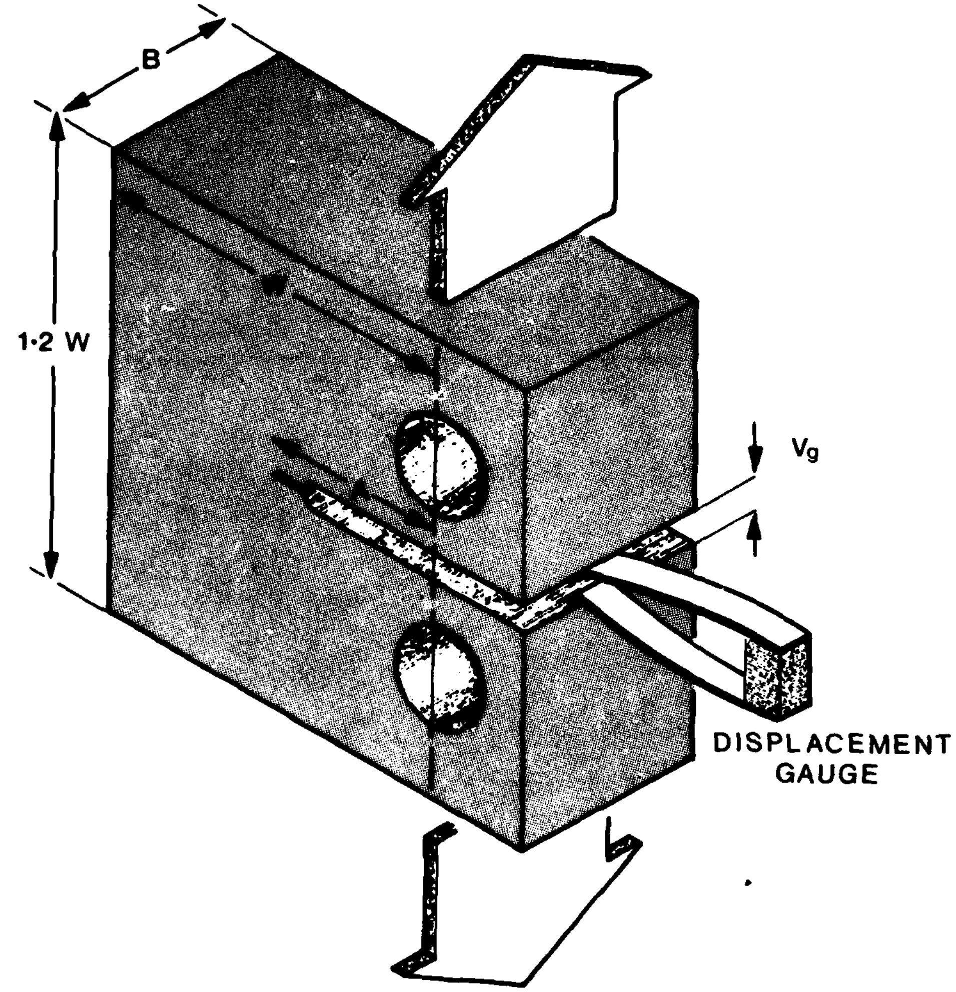

FIG. 1 - The compact tension specimen (CTS) for fracture toughness testing.

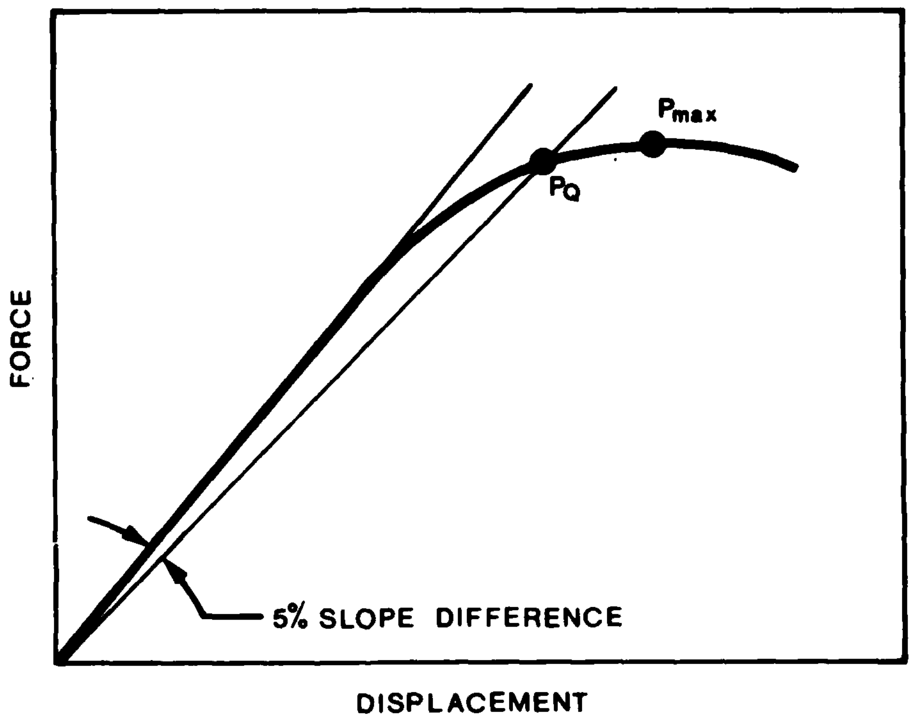

FIG. 2 - Force-displacement trace for fracture toughness test. P_Q, given by a 5% secant, is the critical load, and P_{max} the maximum load.

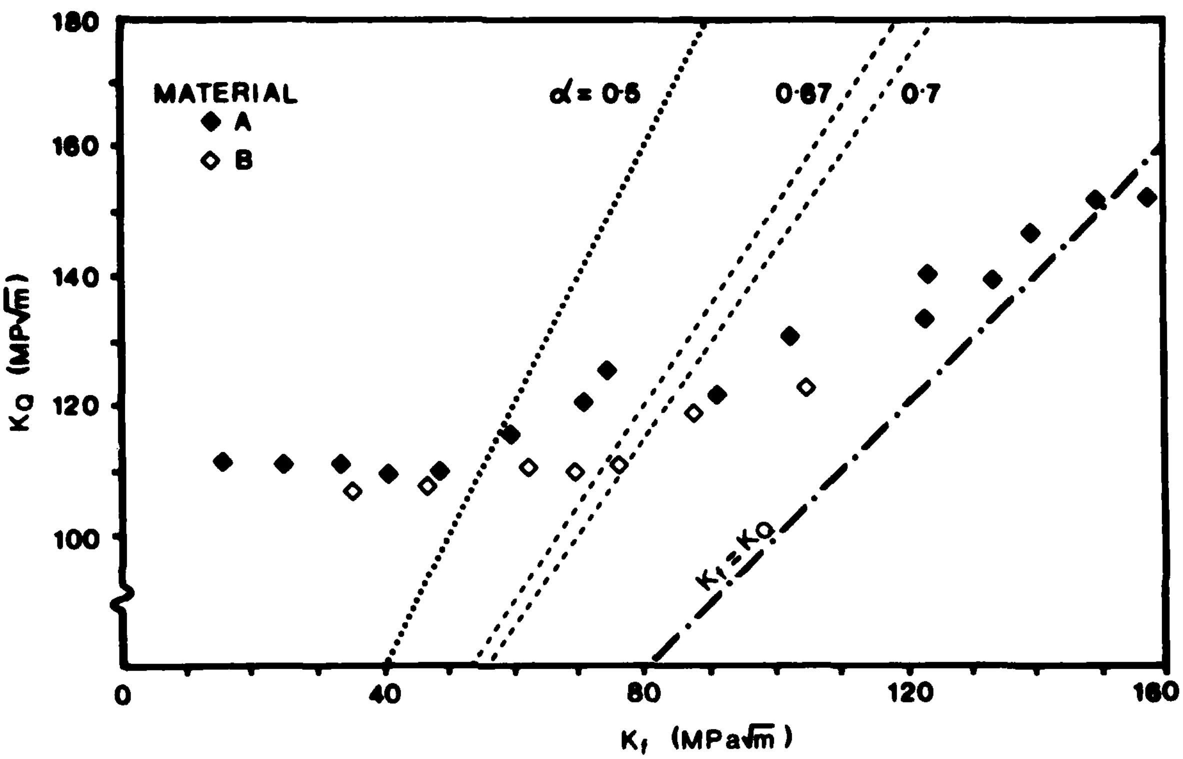

FIG. 3 - Relationship between non-validated fracture toughness, K_Q, and the maximum stress-intensity used during fatigue cracking (K_f), for materials A and B. The relationship $K_f = \alpha K_Q$ is shown for $\alpha = 0.5$ and $\alpha = 1$, in addition to the limiting values $\alpha = 0.67$ and 0.7 specified for plane strain fracture toughness tests.

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